Paper 2/113

DESIGN, FEATURES AND ENGINEERING STATUS OF THE THTR 300 MWe PROTOTYPE POWER STATION

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ABSTRACT

Brown Boveri/Krupp Reaktorbau Ltd. is developing a line of high-temperature helium-cooled pebble-bed reactors, with completely integrated primary system. The feasibility of the concept has been demonstrated by the AVR experimental reactor, which has been supplying electricity to the grid since December 1967. The next stage in the development is the 300 MWe THTR, which has the same design characteristics as the AVR. However, various components were modified because of the increased dimensions of the THTR, such as the prestressed concrete pressure vessel. The design of the THTR, its safety concept, and supporting development tests are described, as well as the status of engineering and construction arrangements.

GENERAL CHARACTERISTICS OF THE 300 MWe THTR

The main activity of the Brown Boveri/Krupp Reaktorbau Ltd. is concentrated on a thorium high temperature reactor line based on spherical fuel elements. The main characteristics of this reactor line are the following:

- spherical fuel elements
- helium as coolant
- high primary gas temperatures up to 800°C
- primary system completely integrated

The spherical fuel element permits continuous fuel loading during operation. Each individual fuel element has a negligible amount of reactivity.

DISCLAIMER

The feasibility and advantages of this reactor concept have been demonstrated by the construction and operation of the AVR experimental reactor (15 MWe) which was brought to criticality for the first time in August 1966. Since December 1967 AVR has supplied electricity to the grid, and during 1969 the plant achieved an availability of 72 %. The thorium high temperature reactor (THTR) possesses essentially the same construction characteristics as the AVR (Slide 1). However, based on the experience gained with AVR, and in view of the higher power of THTR the following components were introduced or changed:

- the prestressed concrete pressure vessel
- the core structure
- the shut-down system
- the fuel element circulating system

The 300 MWe THTR prototype reactor is designed and optimized as a direct predecessor of a reactor of commercial size (Slide 2).

THE INTEGRATED PRIMARY SYSTEM

The reactor core and all main components of the primary system - blowers, steam generators, shut-down system -, excluding the fuel circulating system and gas purification plant, are completely integrated in a prestressed concrete pressure vessel. Access to these components is not foreseen although they can be removed in case of failure or of inspection or maintenance work. All other components and facilities are located outside the prestressed concrete pressure vessel and are accessible during reactor operation (Slide 3).

The reactor core consists of approximately 700 000 spherical fuel elements of 6 cm diameter. The cylindrical core of 5,6 m diameter and 6 m height is formed by a graphite wall which acts as reflector and surrounds the core on all sides. The bottom reflector is conically shaped with an inclination of 30° and opens into a central discharge tube of 800 mm dia.

Graphite is a well-known material proven in many reactors. The THTR reflector is exposed to a higher radiation dose (maximum total dose $2 \cdot 10^{22}$ nvt) and to a considerably higher temperature. Apart from that and in addition to its usual function as a reflector, and as nuclear and thermal shielding, it must perform the mechanical function of a supporting and containing structure for the pebble bed. By an appropriate choice of the graphite (considering the important influence of the cementing resin) it is possible to remain within controllable dimension changes of the structure since the determining fast neutron flux decreases very rapidly in the reflector so that a noticeable shrinkage can occur only up to a depth of 10 - 20 cm of the inner graphite layer. With the selected graphite type and the total maximum dose to be expected a maximum shrinkage of 2 % and an corresponding growth to the initial dimensions was taken as a design basis. Because of all these requirements, special measures for the core structure are necessary, to provide the necessary flexibility of the graphite structure for temperature- and radiation-induced dimensional changes, thus avoiding possible compressive forces while insuring the stability of the total structure. These requirements were met by relatively small blocks specially shaped and arranged in columns and by connecting and fixing the blocks with wedges and dowels (Slide 4 and 5).

The prestressed concrete pressure vessel acting at the same time as pressure vessel and as gas- and pressure tight safety containment, includes all main components of the primary circuit. It is a cylindrical vessel of 16 m diameter and 15 m height with a wall thickness of approximately 5 m. Prestressing is achieved with annular and vertical stressing cables having a guaranteed rupture load of 890 Mp. The prestressing cables are inserted in sheaths embedded in the concrete and are grouted after prestressing to insure sufficient protection against corrosion.

For the pressure vessel a relatively conservative design was selected, which has been proven in numerous large-scale constructions and has been and will be tested in a number of model tests (1:5, 1:45, 1:20). The test result will be incorporated in the large-scale construction. For further projects, while retaining the same vessel shape, various technical and cost-saving improvements are foreseen, such as transition to a horizontal wire winding pre-stressing system and reduction of the inner dimensions by an optimum arrangement of components. It is possible that further economic advantages may result from the podded design; the pressure vessel cost and the technical safety requirements are approximately equal for both vessel types.

For the introduction of blowers, steam generators, absorber rods, pipes, etc. the prestressed concrete pressure vessel is equipped with penetrations. These penetrations are reenforced by shutter-tubes designed to absorb the forces in the area near the penetrations. The largest openings of 2,25 m diameter for the steam generators are located in the top slab of the vessel.

Gas-tightness is achieved by application of a metal liner of 20 - 30 mm thickness serving at the same time as the inner shuttering for the prestressed concrete pressure vessel during construction. For the liner material special properties are required, such as high elasticity, good weldability, and high yield strength.

An insulation on the inner wall and a water cooling system welded on the outside of the liner protect the steel liner and the concrete against excessive temperature effects. As insulation a metal foil insulation (stainless steel) proved to be the optimum solution since with this insulation purity requirements can be easily met, irradiation behaviour of the materials is sufficiently known, mechanical properties are satisfactory, and aging and corrosion are not to be expected. The thickness of the heat insulation of the liner is approximately 70 mm.

Six parallel single-stage radial blowers each supplying one steam generator, circulate the coolant gas. The blower is designed as an insertable unit. The impeller is mounted in an overhung position and is oil-lubricated. A baffer-gas system avoids the penetration of oil into the primary gas. Each blower is equipped with a combined bypass and shut-off valve system to allow connection of a single blower while other blowers are operating, trimming of coolant gas flow through one steam generator under constant blower speed, and shut-off of one line in the event of failure of one steam generator. As drive a bipolar 3-phase squirrel cage motor was selected which is characterized by simple design and high operational safety. Blower power is controlled by variable frequency. Three blowers are supplied by one turbine generator set. In the event of failure of the two turbine sets, operation can be maintained with constant speed by the mains power supply. In addition, transformer sets are provided, permitting start up and emergency operation of individual blowers (Table 1 and Slide 6).

Table 1. Blower Data

Number of units	6
Delivery per circulator	49,25 kp/sec
Delivery in volume	14 m^3/sec
Pressure at suction duct	38,9 ata
Pressure increase	1,1 ata
Temperature at suction duct	250°C
Circulator power	1780 kW

Six steam generators connected in parallel transfer the heat generated in the core to the secondary water-steam-circuit. The main steam generator date are listed in the table (Table 2).

Table 2. Steam Generator Data

Number of units	6
Diameter of tube bundle	2 000 + 55 mm
Height of bundle	max. 12 500 mm
Gasflow through the generator	upwards
Total length	17 800 mm
Output per unit	128 MW
Hot gas temperature	750°C
Cold gas temperature	250°C
Gas pressure	39,35 ata
Pressure drop at gas side	max. 0,45 ata
Gas mass flow	49,25 Kr/sec
Live steam conditions	335°C / 190 ata
Feed water conditions	180°C / max. 240 ata
Reheating	
at entry	365°C / 56 ata
at exit	535°C / 50 ata
Steamflow	153 t/h

The helium flows through the steam generators in an upward direction. The tube bundles of superheater, reheater, evaporator, economizer are arranged in gas flow direction. The steam generator operates in a once-through-system. The water steam-flow through economizer, evaporator, and reheater is in counter-flow direction, the superheater in uniflow direction. Three steam generators are connected in one main group, which is equipped with a common feed-water line, a start up flush-tank, and a common cold reheater line. To insure safe emergency cooling and removal of decay heat from the core each steam generator can be operated independently of the other steam generators, i.e. each is equipped with separate shut off and control valves. Each tube bundle of the steam generator is subdivided into forty independent systems which are individually led through the top slab of the prestressed concrete pressure vessel and connected outside of the vessel. Hence, in the event of a tube failure each system can be isolated from outside. The steam generator is so designed that it can be replaced.

The control and shut-down system is designed so that the reactor load can be varied between 40 and 100 % and the shut-down reactivity required to keep the reactor in the cold critical state is available. Fine control is carried out by 36 rods which are freely moved in bore holes in the reflector. Shut-down of the reactor under both normal and fault conditions is effected by 42 core rods which are directly inserted into the pebble bed. This procedure was verified by extensive tests on a complete model 1:6, 1:10 and on sectional models in 1:1, 1:2, 1:3. This proved that the rods can be directly inserted into the pebble bed under all operating conditions of the reactor and neither the fuel elements nor the absorber rods themselves are exposed to excessive stresses. Each core rod is driven by a pneumatic step drive, achieving safe insertion at a step size of 2 cm and a step frequency of 0,3 sec. For rapid shut-down a long-stroke pneumatic system is provided, with an insertion speed of 30 cm/sec. Each drive has a separate supply system with redundancy (Slide 7).

The THTR fuel element circulating system is of special interest. It is not integrated in the primary circuit and in contrast to reactors with rod type fuel elements, requires no machinery inside the core for charging, exchanging, and discharging fuel elements. For the downward motion of the fuel elements from the core (fuel element discharge) gravity is used and upward movement (fuel element charge) is achieved with pneumatic energy by helium from the primary circuit. For the construction of the fuel element circulating system a building block system, composed of conventional units was used (Slide 8 and 9).

HELIUM TECHNOLOGY

Because of their special requirements, the components involved in the helium system required the development of a new technology which can be roughly divided into three problem areas:

- helium purification and purity
- helium leak-tightness
- lubrication and friction in an extremely pure and dry helium atmosphere

According to the present state of technology, these problems can be considered essentially solved. For selection and application of components, however, a number of aspects must be taken into account, which have proven to be advisable, on the basis of knowledge and experience gained up to now, especially through construction and operation of the AVR. The following aspects are of importance:

- good accessibility to the components needing maintenance (location outside of radiation area)
- good maintenance facilities for systems with flanged and screwed joints (plastic material)
- protection of the sensitive instruments against dust and dirt caused by assembly, through use of suitable filters
- protection of the helium against pollution from the operating components (oil, air, etc.)
- simple and conservative design of systems
- well-defined and separated tasks for individual systems, thus allowing uncomplicated design
- use of conventional proven components

These fundamental aspects partly result from special newly developed designs which were carried out to achieve an optimum solution of the reactor concept of the gas cooled high temperature line.

The mechanical impurities which are mainly produced by the gas circulation plant the fuel element abrasion in the core and the assembly protection and which impair the leak tightness and the control exactness of a number of valves, can be controlled by mechanical filters but even more effectively by restricting or removing the impurity sources. The impurities from the gas circulation facilities can be largely avoided by barrier gas systems or oil free blowers and compressors (gas-bearings blowers, membrane compressors and dry operation compressors). The impurities produced by assembly work are reduced to a minimum by careful assembly (freedom of grease, scale, and corrosion of all helium-carrying systems) in appropriate clean conditions standards. For this purpose pre-assembly in the workshops of the suppliers must be demanded. The dust which is unavoidable due to fuel element abrasion is eliminated by appropriate mechanical filters in the gas purification plant.

The wear problems occuring under these specific reactor conditions are solved by special constructions (cageless ball bearings, special bearing clearances, dry lubricated structures) with appropriate auxiliary measures such as barrier gas systems.

For safety and economy reasons, the problem of leak tightness is of special importance for the HTR. Although welding is the most simple, most economic and safest solution, it is only applicable for static seals and this applies for operational reasons only in some cases. The solution adopted for dynamic seals is to be demonstrated for two especially critical cases, that is gas tightness by valves and gas tightness in the event of rotary motion (momentum of rotation). In both cases a satisfactory solution could be achieved only by redesigning the components in parallel with sealing material and lubricant developments for these components. Because of the favourable development results of plastics materials such as Viton, Kel-F, Vespel, RCH 1000 all now available, which in addition to sufficient radiation and temperature resistance, have satisfactory mechanical properties; the same applies for lubricants.

The first example concerns a simple, safe, and economic gas shut-off bellows valve (leak tightness in the valve cap is achieved by a specially mounted plastic material). (Slide 10)

The second example concerns a gas-tight rotary drive. Also in this case, special importance was attached to safety and economy. In this type of solution, the gas tightness is achieved by using grease which forms a considerably less complicated fluid seal. Higher pressure relative to system pressure, grease expansion due to temperature changes, and re-lubrication are effected by pressure reservoirs (Slide 11).

SAFETY CONCEPT

In this connection only those facts will be mentioned, in which the safety concept of THTR differs from those of other reactors. The decisive safety aims are:

Complete integration of the primary coolant circuits in the prestressed concrete pressure vessel

- hence limited loss of coolant in the event of credible accidents
- release of activity via ventilation stack in the maximum credible accident
- no sudden depressurization of core
- integrity of core structure

The penetrations in the concrete vessel are designed to prevent activity release by either

- two pressure-tight covers or
- an outer pressure-tight cover, and an inner flow limiting cover (about 33 cm^2 corresponding to a coolant pipe diameter of 65 mm) which, in the case of the outer cover being damaged, restricts the escaping coolant flow to a precise value.

Those primary coolant pipes which lead from the concrete pressure vessel to the auxiliary circuits are ≤ 65 mm diameter. These pipes are double walled as far as the fast action safety release valves. The safety container has no safety valves and is designed for the pressure of the maximum credible accident. The total primary building is divided into three categories of rooms, according to their different activity levels (Slide 12).

- Rooms continuously accessible during operation
- Rooms accessible only for a short time during operation, for inspection purposes
- Rooms not accessible during operation, access possible only after partial or total shut-down of plant

The third category includes primarily the room for the installation of the fuel circulating plant and part of the room for the gas purification plant as well as the space between air duct and prestressed concrete pressure vessel. According to their room categories, these rooms are separately ventilated and are connected to the ventilation stack via the normal exhaust air system and in addition, by a pressure safety system.

The safety analysis of this concept showed that, the maximum credible accident, with reference to endangering the surroundings, requires two independent faults to occur, namely

- a break in a primary coolant pipe (≤ 65 mm $\emptyset$) outside the concrete pressure vessel
- the simultaneous malfunctioning of the safety release valve in that pipeline

In this case the escape of coolant gas is relatively slow, without a noticeable pressure rise in those rooms and can easely be vented. Even in the case of this maximum credible accident, the allowable contamination of the surroundings is not reached.

The largest realistic reactivity excursion through

- the accidental withraval of the two most effective control rods from the core

the largest realistic coolant disturbance by

- the simultaneous breakdown of three blowers, and

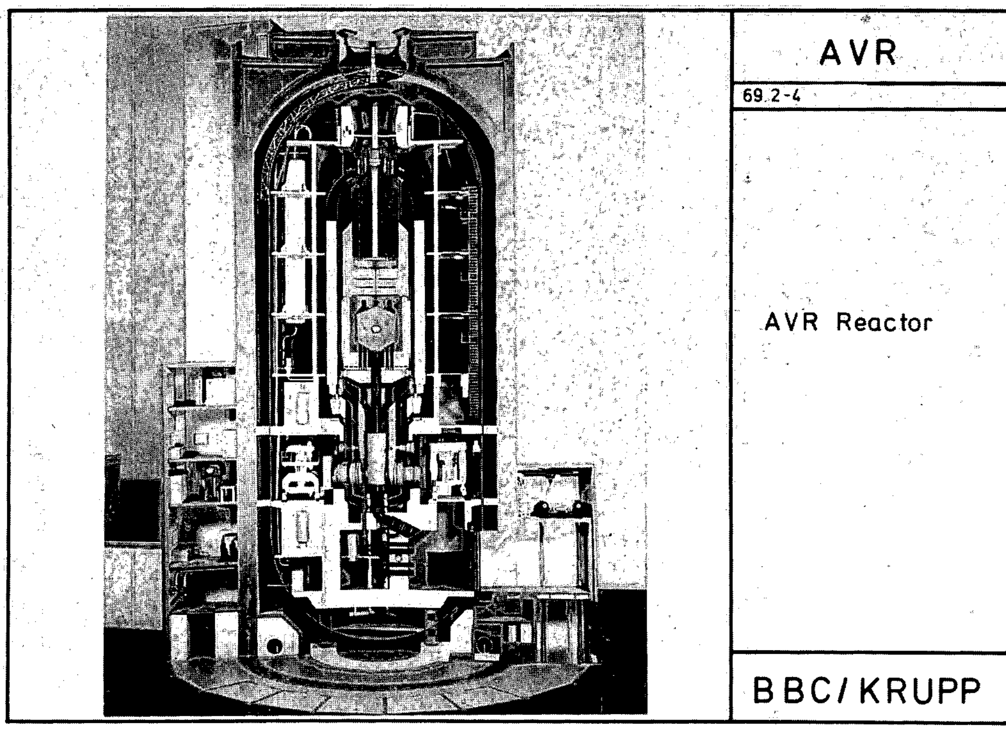
the largest realistic pressure change through

- the burst of a steam generator pipe and causing water ingress into the core

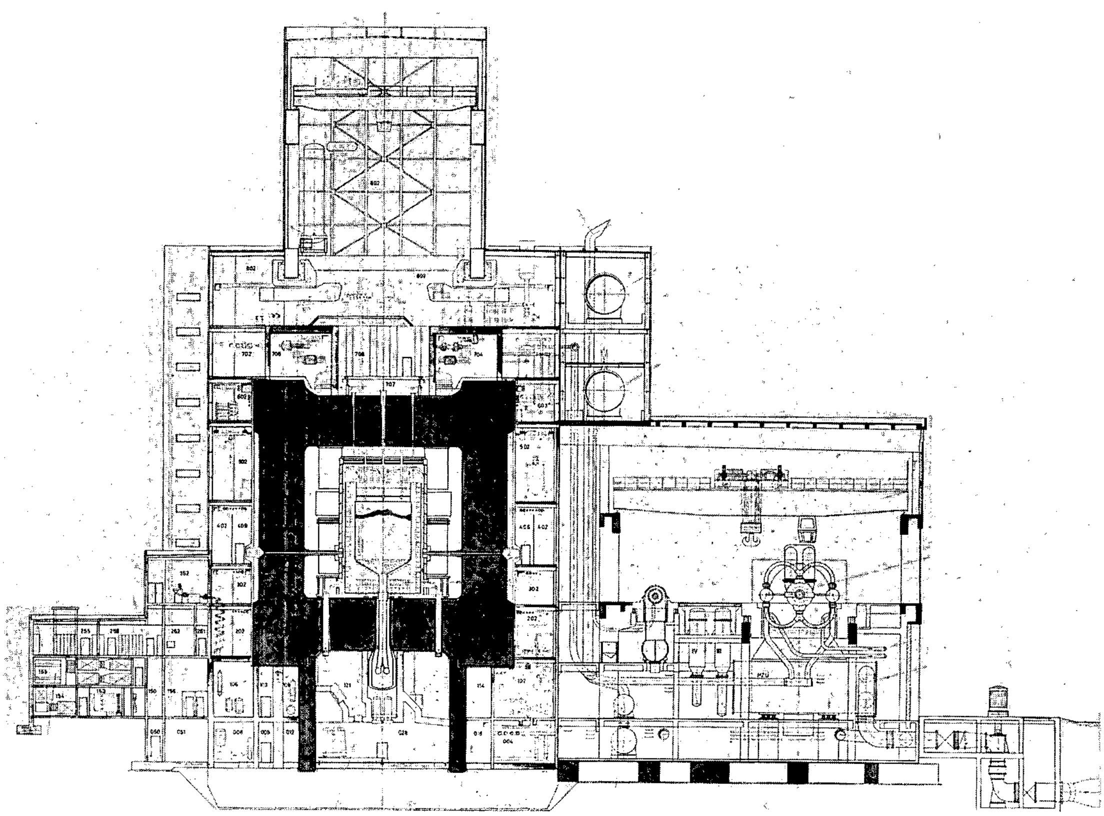
have such a limited effect on the reactor, that the surroundings are not endangered.

THE STATUS OF THE 300 MWe THTR-PROTOTYPE

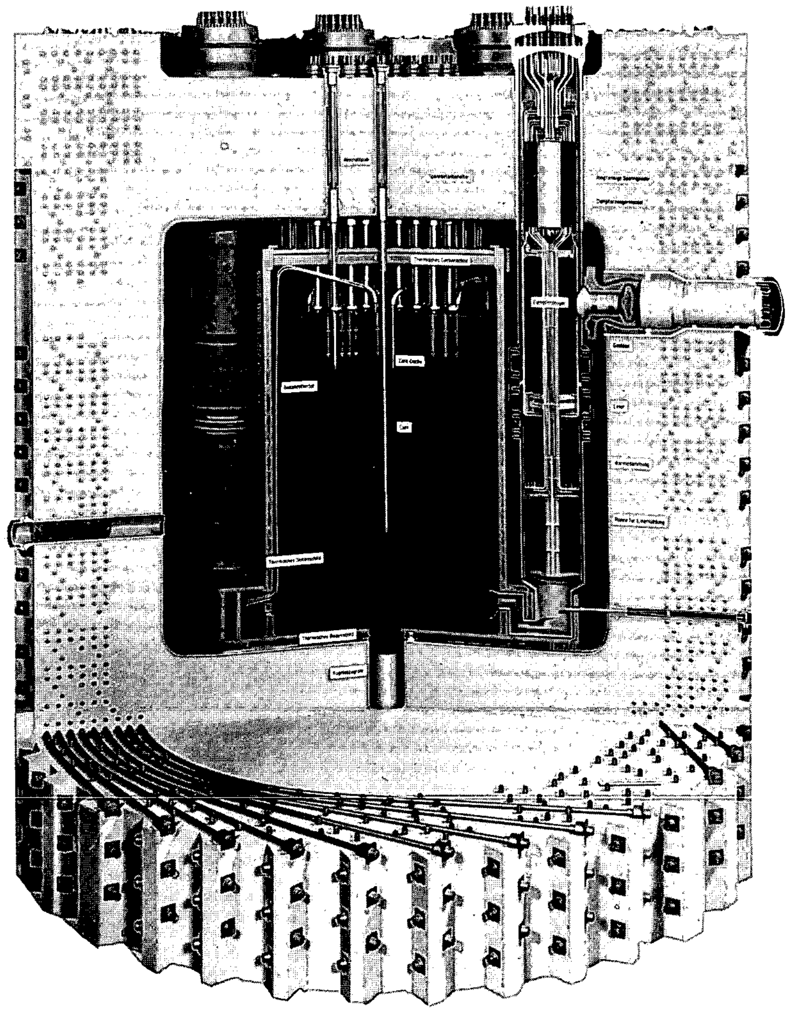
Construction documents for this prototype plant have been completed and an offer has been submitted. The licensing procedure has been initiated early 1970 (15/1). A utility group for the operation of this reactor plant has been founded and construction work is to be started in the beginning of 1971. The construction period is 5 years, including a test run of the plant of three month.



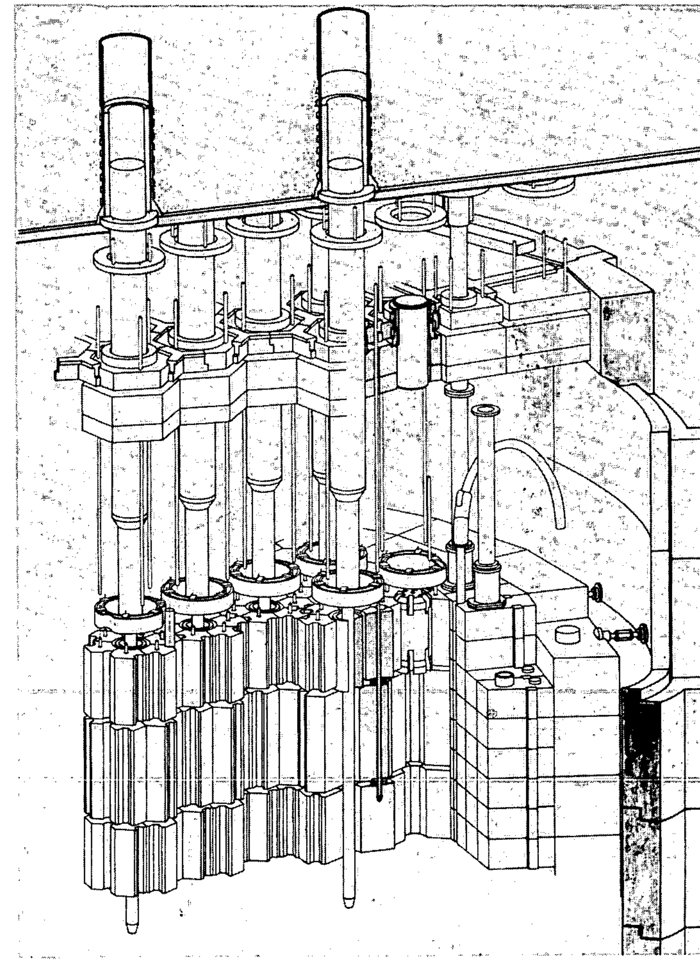
1 AVR Reactor Sectional View



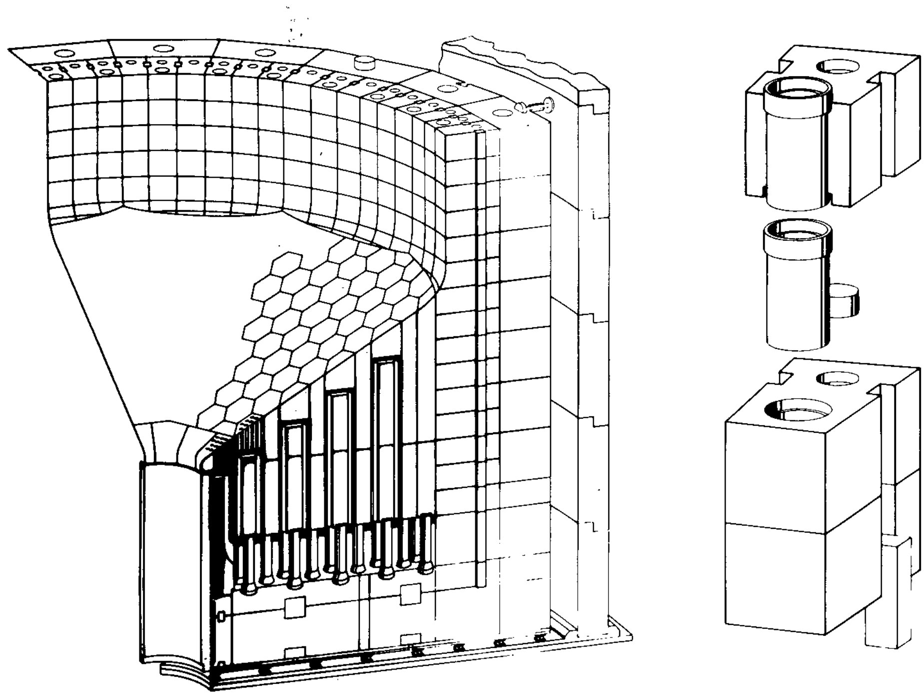
2 THTR Section



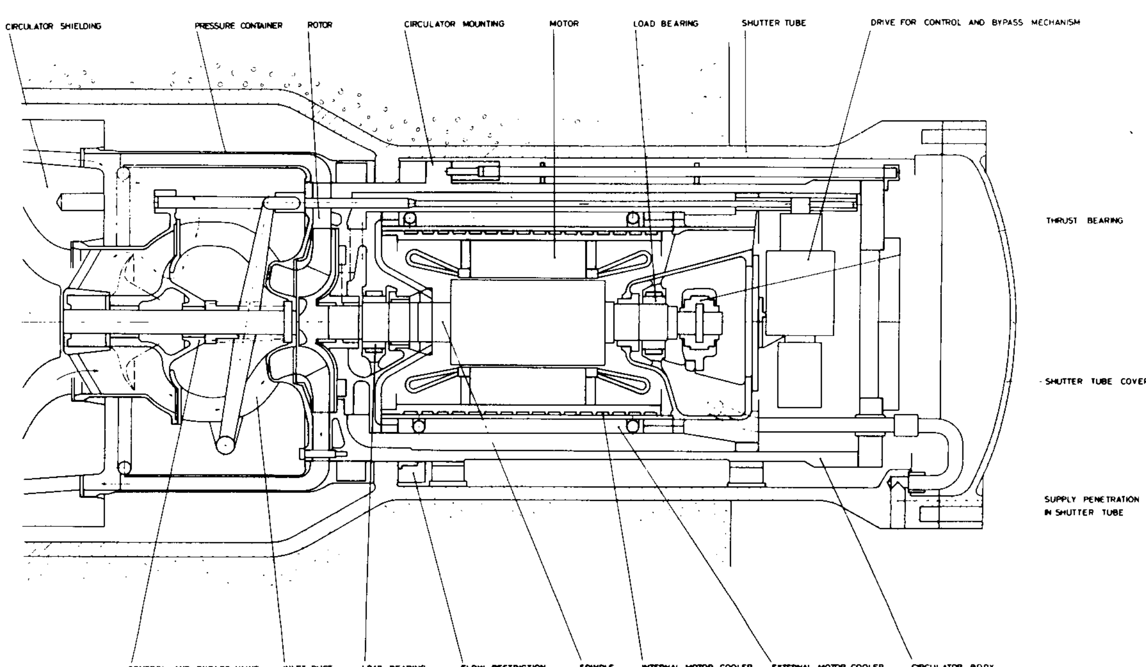
3 Prestressed Concrete Pressure Vessel (Model) of THTR Power Plant with Steam Generators, Blowers, Core, Absorber Rod, Facility etc.



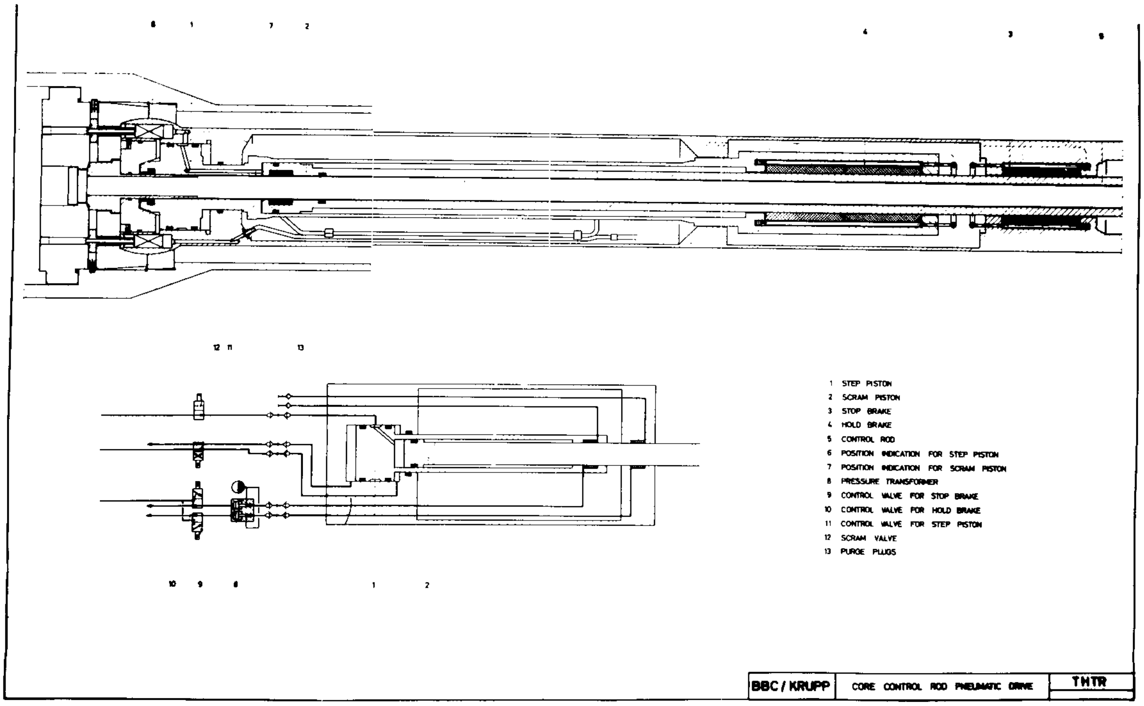
4 Graphite Structure-Ceiling



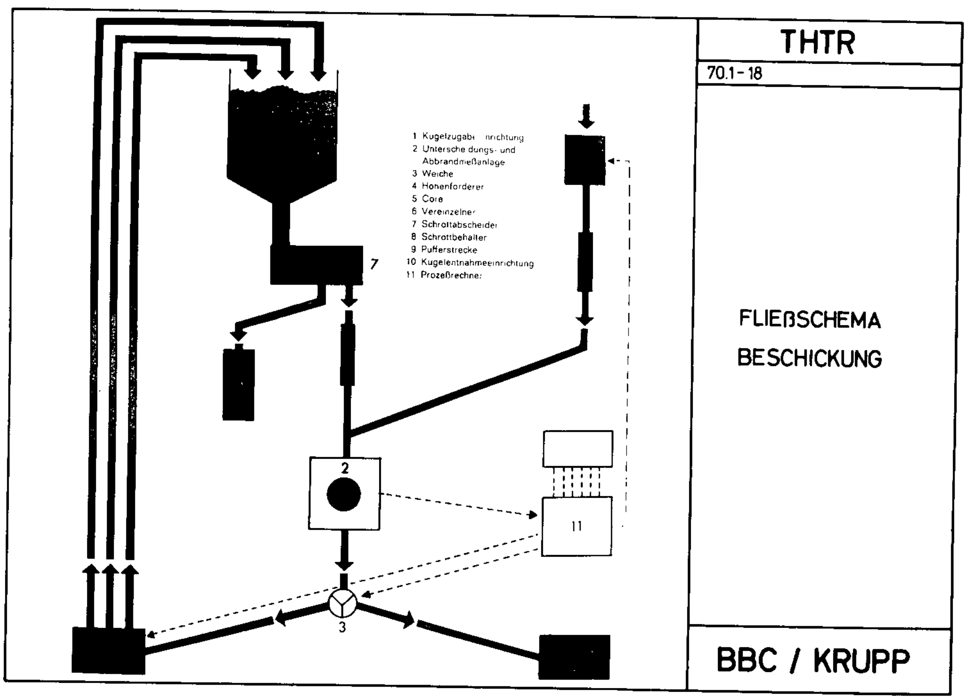
5 Graphite Structure-Bottom



6 Blower Section



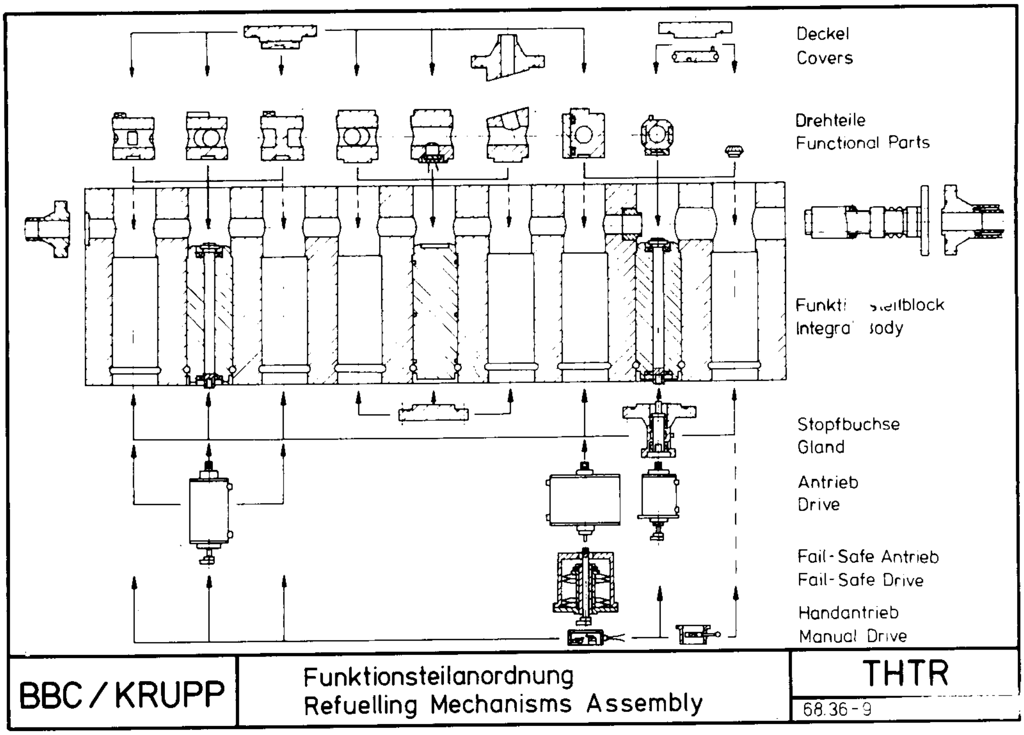
7 Section of Core Rod Drive



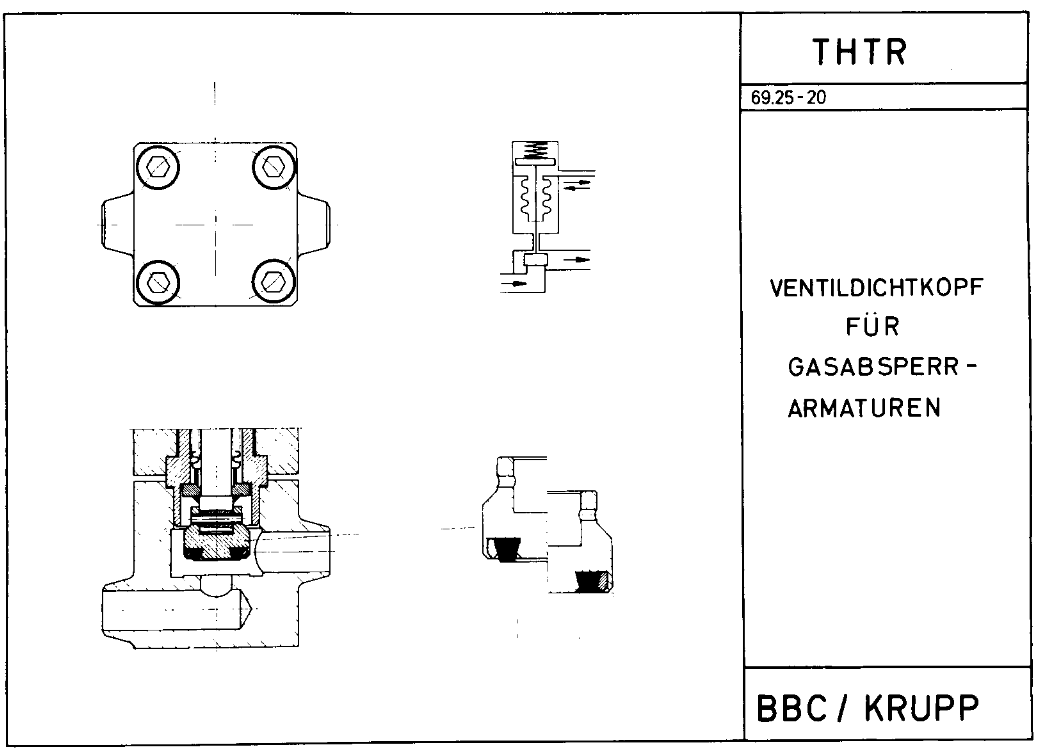
8 Fuel Circulating System * (Flow Diagram)

*8 (Photo No.)

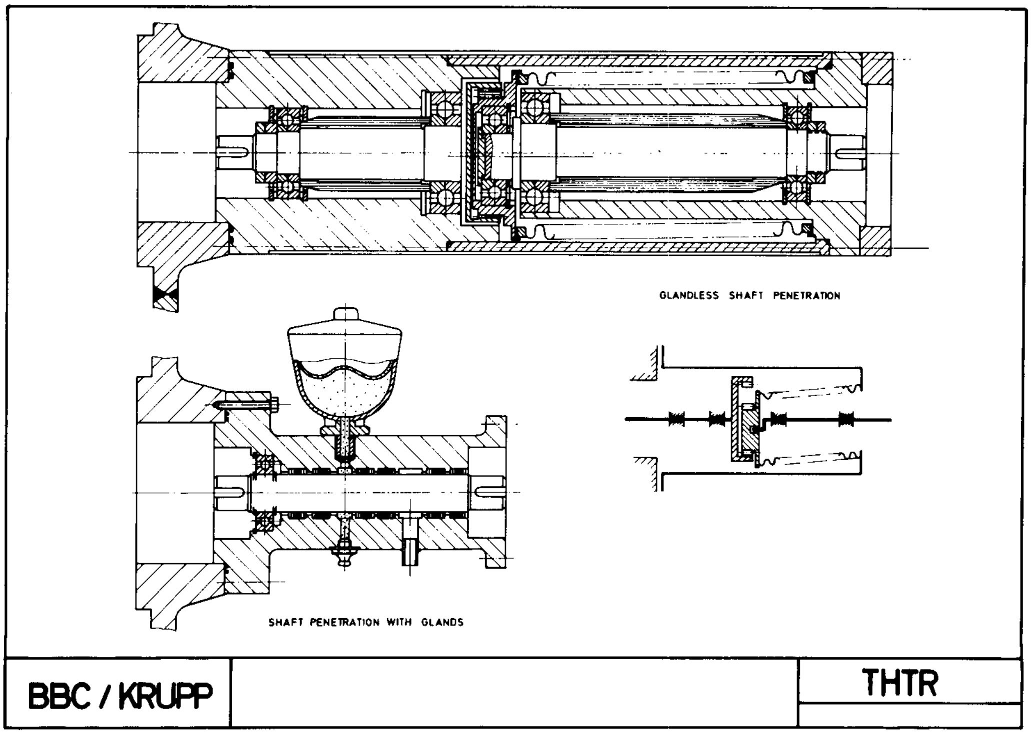
1- Fuel Element Charge Equipment
2- Burn-up Measurement
3- Switch
4- Pneumatic Elevating Device
5- Core
6- Singulizer
7- Demaged Sphere Separator
8- Demaged Sphere Container
9- Buffer-zone
10- Discharge of Spent Fuel
11- Process Computer



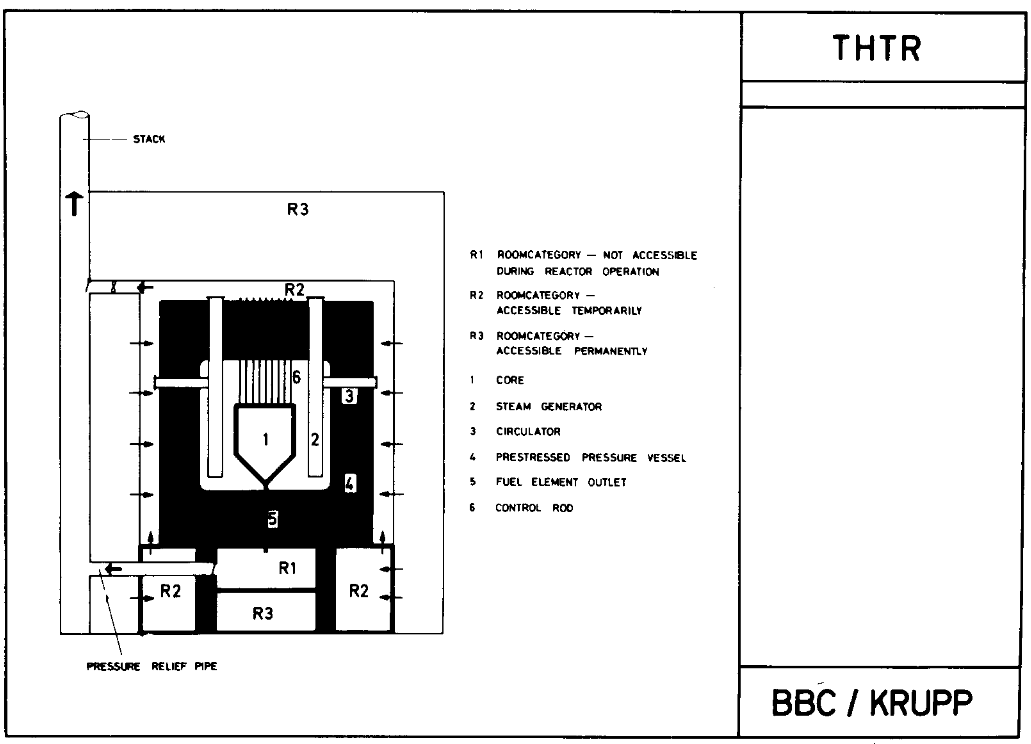
9 Fuel Circulating System - Building Block System



10 Gas shut-off Valve



11 Rotary Drive



12 Safety Concept

DISCUSSION

B. N. Furber: I would like to have further details of the metallic insulation. In the experience of TNPG this insulation suffers from at least two weaknesses: (1) It is highly anisotropic, (2) it is very difficult to design to accept interface pressure gradients. In the circulator outlet these two weaknesses are likely to seriously affect the insulation performance. What test work has been carried out in this area?

J. Schöning: We are aware of the problems raised by you and our people have a concept to overcome them, the details of which we are not able to present. There are extensive experiments and detailed design work going on to confirm the concept that has been selected.

R. D. Vaughan: The THTR reactor section shows the boilers to be of cylindrical plan form, but located in the pressure vessel vault along with the reactor core. May I conclude that the designers have looked at the alternative with pods in the wall of the pressure vessel and found it would be more expensive?

J. Schöning: The design of the THTR pressure vessel and the arrangement of the boilers within the vessel was already decided upon in 1965. At that time the pod-type vessel did not yet seem to be evaluated. At this time a change of the concept is not possible due to the advanced state of development and design. It is important, however, that the THTR-vessel allows the removal of the boilers in the same way as the pod-type vessel does. Within the development work for a large commercial power station a detailed comparison of the two vessels and their influence upon the plant is under way.

M. Dalle Donne: Coming back to the question of Dr. Furber, I think he answered his question himself with his paper. With helium one is in the region of Raleigh number where the Nusselt number is constant, so that a variation of helium velocity does not change the heat transfer coefficient of the insulation; although this may be the case with CO_2, where the heat is mainly transferred by convection, while with helium it is transferred by conduction.